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FIELD MEASUREMENTS OF INTERRILL EROSION UNDER DIFFERENT SLOPES AND PLOT SIZES

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ABSTRACT

Despite numerous studies, the effect of slope on interrill erosion is not clearly established. Several interactions exist between erosion parameters that are not taken into account under experimental laboratory measurements and results need to be validated in the field. The influence of slope steepness (2 to 8 per cent) on soil loss for a crusted interrill area and the detachment and transport processes involved in the interaction between slope, rain characteristics and plot size were investigated. Sediment discharge and runoff rates were measured in bounded plots (1 m^2 and 10 m^2) under natural and simulated rainfall, allowing the analysis of a combination of detachment and transport processes at various scales in the field. Runoff rate increased from 20 to 90 per cent with increasing slope and rain intensity for both plot sizes, whereas sediment concentration increased from 2 to 6 g l^{-1} with increasing slope only for the 10 m^2 plots. At the 1 m^2 scale, erosion was transport-limited due to the reduced rain-impacted flow. Interactions between slope angle and rain intensity were observed for detachment and transport processes in interrill erosion. Results show the importance of an adapted experimental set-up to get reference data for interrill erosion model development and validation. Copyright © 2000 John Wiley & Sons, Ltd.

KEY WORDS: interrill erosion; slope; field measurements; runoff velocity; detachment and transport processes

INTRODUCTION

Contradictory results describing the effect of slope on runoff and interrill erosion are reported in the literature. Poesen (1984) observed a decrease in runoff with increasing slope. This was related to either a thinning of the crust or to its erosion by rilling. Bryan and Poesen (1989) and Slattery and Bryan (1992) also found that rilling increased infiltration. De Ploey *et al.* (1976), Sharma *et al.* (1983) and Djorovic (1980) observed an increase in runoff with increasing slope angle and this was attributed to a decrease in depressional storage and ponding depth. Govers (1990) showed that slope had a significant negative effect due to differential soil cracking. Fox *et al.* (1997) attributed the decrease in infiltration with increasing slope angle to greater ponding depth on spatially varying seal properties. However, Lal (1976) and Mah *et al.* (1992) did not find any significant effect of slope angle on runoff.

These discrepancies may be caused by the variability in experimental conditions for the reported results (Fox *et al.*, 1997). Slope range, rainfall intensity, plot size and soil characteristics may affect the results significantly. Thus, empirical results should be discussed with regard to the physical processes involved for each experimental set-up.

Palmer (1964) and Moss and Green (1983) showed that detachment by splash decreased with increasing ponding depth. The water layer protects the soil surface from drop impact when it exceeds a thickness of about two drops' diameter (Ferrera and Singer, 1985). This could explain an increasing erosion rate with increasing slope angle. An increase in splash erosion with increasing slope has been observed by Fox and Bryan (1999) and the theoretical basis for this can be found in Torri and Poesen (1992).

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Another reason could be the increase in runoff velocity (Gerits and De Lima, 1990) and the smaller angle between raindrop impact and soil surface for steep slopes (Gerits, 1990). Fox and Bryan (1999) attribute the increase in interrill erosion with slope to the effect of slope on runoff velocity. Soil loss was found to be linearly related to flow velocity. Kinnell and Cummings (1993) mentioned a possible indirect effect of slope related to the variability of aggregate stability and soil crustability in relation to topographic parameters.

In erosion models, slope angle was taken into account within the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978) on the basis of statistical data (Neal, 1938). Attempts are now in progress to consider the physical basis of the slope effect, for example in the Water Erosion Prediction Project (WEPP) (Nearing *et al.*, 1989), EUROSEM (Morgan *et al.*, 1998); flow transport model (Kinnell, 1988, 1991) and stream power based model (Hairsine and Rose, 1992). However, several interactions between slope angle, runoff and erosion exist and need to be identified. In addition, experimental laboratory measurements need to be validated in the field.

The objectives of this study were to analyse the effect of slope angle on interrill erosion for different plot sizes (1 to 10 m^2) and to identify possible detachment and transport processes involved in the interactions between slope, rain characteristics and plot size. Runoff rate, flow velocity and sediment delivery were measured in the field under different slopes and plot sizes for both natural and simulated rainfall. Rain-impacted flow conditions were also compared to flow conditions only.

MATERIALS AND METHODS

Site description

The study was conducted in an experimental field located in the northwest part of the Paris basin (Pays de Caux). The site is characterized by silty loamy soils (Luvisols) which are very prone to soil crusting because of their low clay (120 ± 2 g kg^{-1}) and organic matter (14 ± 3 g kg^{-1}) contents (Le Bissonnais and Bruand, 1993). The experimental field was about 100 m in length and located in the middle of a convexo-concave catena with slope gradients of about 2, 4, 8 and 2 per cent from top to bottom. Three 1 m $\times$ 1 m bounded plots were established at three positions (2, 4 and 8 per cent) along the catena. Two additional 2 m $\times$ 5 m bounded plots were installed at the 4 and 8 per cent slope positions. Soil surface texture and organic matter content did not significantly vary along the slope between the different positions.

Surface conditions

The plots were tilled and cultivated with winter wheat sown late in September 1994. Vegetation cover was about 10 per cent at the time of the measurements. Measurements were made during February and March 1995 on a field that had received 450 mm of rain since sowing. A well developed surface crust had formed as a result of the low aggregate stability of the loamy material. No significant soil cracking was observed during the period of experimentation. Interrill erosion occurred frequently in winter because of continuous low intensity rainfall. Rill erosion occurs rarely and only during important rainstorms. No rills were present in the experimental plots. Surface microtopography and crust morphology did not vary during the studied period (January to May 1995). Therefore, measurements were considered to be obtained under steady-state interrill erosion conditions.

Natural rainfall events and rainfall simulation characteristics

In the studied area, rainfall intensities are generally low with means between 1 and 5 mm h^{-1}. A rainfall of 20 mm with an intensity between 5 and 10 mm h^{-1} has a 3-year return period. Six natural rainfall events were studied. In addition, rainfall simulation was applied on the same plots. Simulated rainfalls were obtained with an ORSTOM simulator (Valentin,1978), consisting of an oscillating nozzle (Teejet SS 6560) located 3·5 m above the plots. A 30 mm h^{-1} rainfall intensity was first applied for 30 min before measurements in order to obtain steady-state conditions of runoff and erosion. Immediately after, the plots were subjected to simulated rainfall during three 30 min simulations. For the 1 m^2 plots, rainfall intensities were successively 10 mm h^{-1},

30 mm h^{-1} and 50 mm h^{-1}. Only the 30 mm h^{-1} rainfall intensity was applied on the 10 m^2 plots. Drop impact energy was 15 J mm^{-1} m^{-2} for 10 mm h^{-1} simulated rainfall and did not significantly increase for higher intensities because of constant drop size.

Runoff and erosion measurements

For simulated rainfalls, runoff volume measurements and sample collection were made continuously. Collected samples were dried and weighed for sediment concentration. Erosion was calculated as the product of the runoff volume and the sediment concentration. For natural rainfall, total runoff and soil loss were collected after each event.

Flow velocity measurement

Flow velocity measurements were made by injecting a salt solution (45 g l^{-1} NaCl) coloured with Fluorescein at various positions within the 10 m^2 plots. The evolution in electrical conductivity of the runoff was measured at the outlet of the plots after each salt solution injection. The peak in electrical conductivity corresponds to average flow velocity. Flow velocity was calculated by dividing the distance between the injection and outlet points by the time difference between injection of saline solution and peak in electrical conductivity:

$$V(x) = \frac{d(x)}{T_f(x) - T_o(x)} \tag{1}$$

where $V(x)$ = flow velocity, $T_f(x)$ = final time at which the solute passed by a sensor when the signal peaked and $T_o(x)$ = initial time at which the solution was injected.

The electronic component time reaction was neglected (<1 μs). Salt diffusion in water is quite rapid, close to 5 cm^2 s^{-1} in standing water and even more in turbulent water; splash action can have an equally significant action. However, diffusion and splash processes occur in all directions (to the top and the bottom of the experimental plot) and the peak position was supposed not to vary significantly.

In addition, the effect of raindrop impact on sediment concentration was observed during a 30 mm h^{-1} simulated rainfall intensity. Measurements were realized on a 10 m^2 plot with 8 per cent slope and bare soil surface. Sediment concentration under rain-impacted flow conditions was compared to sediment concentration under flow conditions without raindrop impact (surface protected with a porous plastic film).

RESULTS

Natural rainfall characteristics

During the studied period, six rain events were studied corresponding to a total rainfall amount of about 100 mm. A rainfall event characterized by 8 mm h^{-1} intensity and total recorded rain of 16 mm was observed during 16–17 February 1995. The other five events had lower mean intensities and various total rain values: 2 February (1·45 mm h^{-1}; 2 mm); 16 February, 12·00 h (1·44 mm h^{-1}; 46 mm); 16 February, 23·00 h (1·55 mm h^{-1}; 5 mm); 8 March (1·67 mm h^{-1}; 14 mm); 9 March (1·31 mm h^{-1}; 5·4 mm). Intensities and total recorded rain were typical of the winter season.

Runoff

Runoff rates for the 1 m^2 plots under natural and simulated rainfall with slope steepness ranging from 2 to 8 per cent and rainfall intensities ranging from 1 to 50 mm h^{-1} are shown in Figure 1. Runoff coefficients expressed as a percentage of the applied rain are presented to allow comparison between results for different rain intensities. Runoff coefficients under both natural and simulated rainfall were very high. Every natural rain event with more than a 1 mm h^{-1} intensity produced runoff. Mean runoff coefficients ranged from 20 per cent to more than 90 per cent. Runoff coefficients increased with increasing intensity.

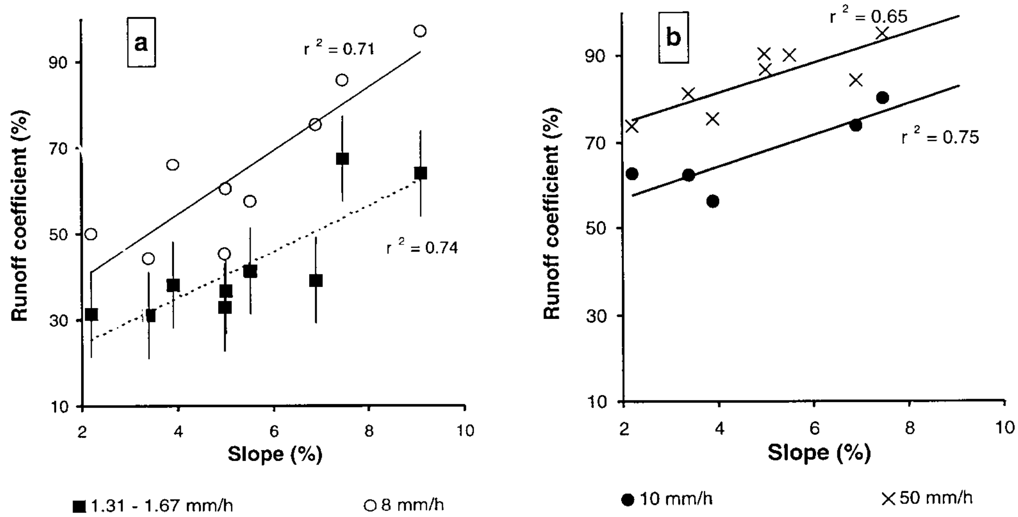

Figure 1. Runoff coefficients for natural (a) and simulated (b) rainfall for different slopes. For natural rainfall, points for intensities ranging from 1·31 mm h^{-1} to 1·67 mm h^{-1} represent the mean of five values and bars show standard error. For simulated rainfall, a point represents the mean of the last four values of steady-state runoff

Runoff coefficients also increased significantly with increasing slope steepness for both natural and simulated rains. For example, runoff ranged from 45 to 85 per cent for 8 mm h^{-1} natural rainfall and from 75 to 85 per cent for 50 mm h^{-1} simulated rainfall.

Measurements for 10 m^2 plots for 4 and 8 per cent slopes (Table I) were consistent with the 1 m^2 plots results.

Sediment concentration

Sediment concentration for the experiments under natural and simulated rainfall are shown in Figure 2. Under natural rainfall conditions, sediment concentration ranged between 3·5 and 5 g l^{-1} for lower intensities and between 6 and 9 g l^{-1} for the 8 mm h^{-1} intensity. Under simulated rainfall, sediment concentrations were

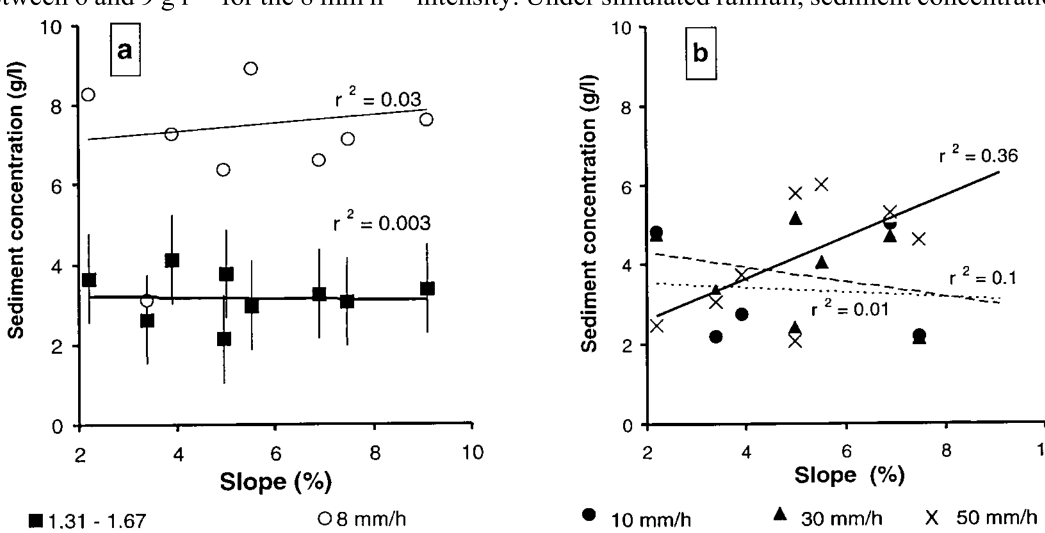

Figure 2. Sediment concentration versus slope angle for natural (a) and simulated (b) rainfall. For natural rainfall, points for intensities ranging from 1·31 mm h^{-1} to 1·67 mm h^{-1} represent the mean of five values and bars show standard error. For simulated rainfall, a point represents the mean of the last four values of steady-state runoff

Table I. Comparison of runoff and erosion measurements for two plot sizes and slopes (30 mm h^{-1} simulated rainfall).

Slope (%)	Surface area (m^2)	Runoff coefficient (%)	Sediment concentration (g l^{-1})	Soil loss (g $m^{-2}h^{-1}$)
4	1	57	3·5	60
4	10	60	4·0	70
8	1	89	3·6	90
8	10	92	7·0	190

in the same range for all intensities and they were lower than for natural rainfall due to reduced and constant kinetic energy. At the 1 m^2 scale, an increase in sediment concentration was observed with increasing rainfall intensity only for natural rainfall.

Slope had no significant effect on sediment concentration at the 1 m^2 scale, despite a slight increase in sediment concentration with slope for the 50 mm h^{-1} rainfall. This contrasts with the significant increase in sediment concentration with slope for the 10 m^2 plots (Table 1). At 4 per cent slope, sediment concentration values were similar for both the 1 and 10 m^2 plots, whereas at 8 per cent slope, sediment concentration for 1 m^2 plots was about half that of 10 m^2 plots for the same runoff rate. The 1 m^2 values remained unaffected by slope but the 10 m^2 values increased substantially.

Soil loss

Soil loss rate was calculated as the product of sediment concentration and runoff amount for a unit surface area and for 1 h of rain. Soil loss rates for the experiment under natural and simulated rainfall are shown in Figure 3. Soil loss increased significantly with the increase in slope steepness from 2 to 8 per cent. Soil loss increased more rapidly with slope at the higher rainfall intensities for the 1 m^2 scale. Soil loss for low natural rainfall intensities was about 2 g m^{-2} h^{-1}, for all slopes, whereas erosion increased from 15 g m^{-2} h^{-1} to more than 50 g m^{-2} h^{-1} for the 8 mm h^{-1} event. Under simulated rainfall, the increase in soil loss with slope was greater for the higher rainfall intensities: soil loss ranged from 10 g m^{-2} h^{-1} for the 2 per cent slope and 10 mm h^{-1} rain to 270 g m^{-2} h^{-1} for the 8 per cent slope and 50 mm h^{-1} rain.

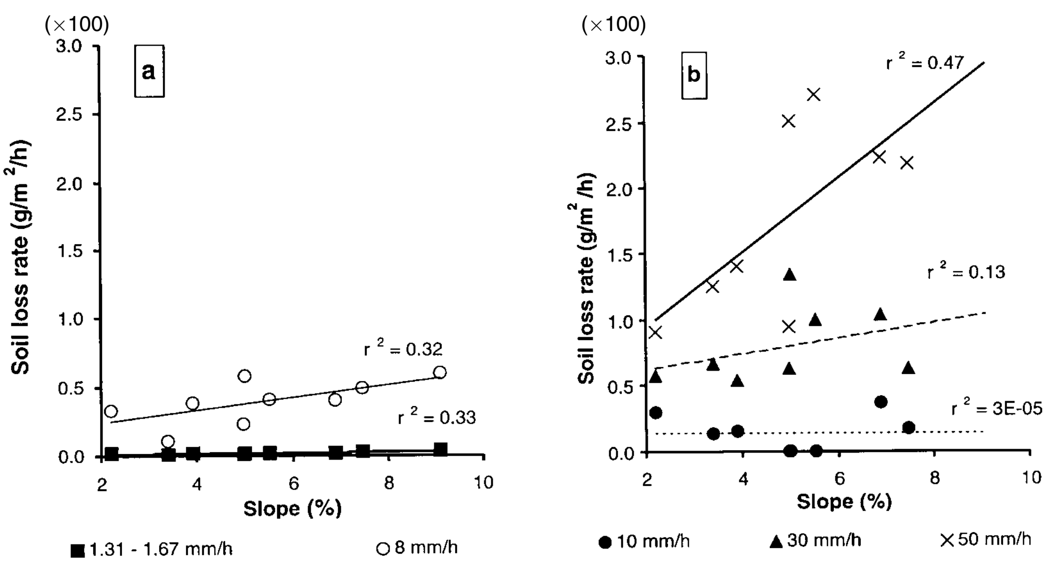

Figure 3. Soil losses for natural (a) and simulated (b) rainfall intensities for different slopes. For natural rainfall, points for intensities ranging from 1·31 mm h^{-1} to 1·67 mm h^{-1} represent the mean of five values. For simulated rainfall, a point represents the mean of the last four values of steady-state runoff

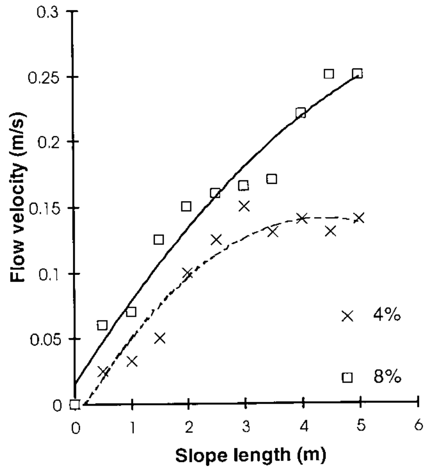

Figure 4. Flow velocity versus slope length for 4 per cent and 8 per cent slopes. Measurements were made on two 10 m^2 bounded plots under 30 mm h^{-1} simulated rainfall intensity. Each point represented the mean of four replicates

Soil loss rate increased more rapidly for 10 m^2 plots than for 1 m^2 plots (Table I), with values up to 193 g m^{-2} h^{-1} for the 8 per cent slope with 30 mm h^{-1} rain.

Flow velocity

Flow velocity was measured on 10 m^2 plots under 30 mm h^{-1} simulated rainfall. Flow velocity was greater for the 8 per cent than for the 4 per cent slope at all slope lengths (Figure 4). Slope steepness affected flow velocity only slightly at 1 m length. However, at longer distances, the flow velocity increased more rapidly for the steepest slope. Equilibrium velocity was reached after 3 m on the 4 per cent slope and still not reached on the 8 per cent slope at 5 m.

Raindrop impact

The effect of raindrop impact on sediment concentration was investigated on the 8 per cent slope: 10 m^2 plots under 30 mm h^{-1} simulated rainfall. Figure 5 indicates that sediment concentration can be reduced to one-third for a runoff velocity of 0·15 m s^{-1} if raindrop impact is removed.

DISCUSSION

The results of the study using smooth crusted surfaces under natural and simulated rainfall at 2 to 8 per cent slopes indicate that (i) slope steepness and rain intensity have a significant effect on runoff for both plot sizes, and (ii) sediment concentration is affected by slope steepness only for the larger plots. This effect can be related to the influence of flow velocity on transport capacity. A significant part of the transport capacity can be attributed to the rain-impacted flow transport. These results agree with those of various authors for laboratory experiments (Lal, 1976; Loch, 1984; Meyer and Harmon, 1989; Kinnell, 1990; Huang, 1998), and are discussed separately below.

Runoff

The increase in runoff with slope was observed for example by De Ploey *et al.* (1976), Sharma *et al.* (1983) and Djorovic (1980). One hypothesis is the reduction in infiltration due to a decrease in the proportion of ponded, surface area, flow depth and detention times at greater slope (Ferrera and Singer, 1985; Fox *et al.*, 1997).

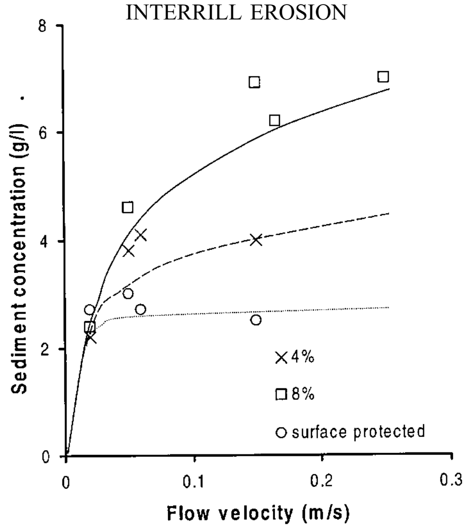

Figure 5. Effect of rain-wash and wash on sediment concentration. Measurements for protected surface were made on a 10 m^2 plot with 8 per cent slope under 30 mm h^{-1} simulated rainfall intensity. Each point represented the mean of four replicates

In the study presented here, flow depth and detention capacity were very low because of initially smooth crusted surfaces. Infiltration rates can be calculated from runoff rates and rainfall intensity. As slope increased from 2 to 8 per cent, infiltration decreased from 1 to 0·5 mm h^{-1} for low intensity natural rains, from 4 to 1 mm h^{-1} for 8 mm h^{-1} natural rain, and from 15 to 5 mm h^{-1} for 50 mm h^{-1} simulated rainfall. Increase in flow velocity with slope steepness and length (Figure 4) may explain the slope effect on runoff. The increase in infiltration with slope observed by others (Poesen, 1984) probably results from rilling (Fox *et al.*, 1997). No rills occurred in our study which probably accounts for the negative trend. The slope effect on runoff was the same for both the 10 m^2 and 1 m^2 plots, though the 10 m^2 plot showed a slightly greater increase. Scale effect on runoff does not appear to be important for the range of scales observed.

Sediment concentration

Sediment concentration was affected by slope only for the larger plots (Figure 2). Measurements presented here show that flow velocity and raindrop impact, which are the main agents responsible for particle detachment and transport (Walker *et al.*, 1977; Huang, 1995), are less efficient at the 1 m^2 than the 10 m^2 scale. At 1 m^2, detachment by raindrop impact occurs but erosion is transport-limited due to low flow velocity ($<$ 0·1 m s^{-1}). The short length of the 1 m^2 plots does not allow flow velocity to increase sufficiently to reveal a slope effect.

On 10 m^2 plots, flow velocity increased to greater values with slope length. However, sediment concentration was significantly influenced by slope steepness itself: it was lower for 4 per cent plots than for 8 per cent plots for the same 0·16 m s^{-1} flow velocity. This result may be explained by Hairsine and Rose's (1992) model which predicts better transport and remobilization of particles by rain-impacted flow processes at steeper slopes. Soil surface slope acts through the addition of a gravity component to the drop detaching force (Kinnell,1990; Torri and Poesen, 1992). The results are consistent with the theory of interrill erosion based on raindrop-induced flow transport (Kinnell, 1988, 1990, 1991).

A rough mapping of flow velocity spatial variability at the plot scale shows that runoff followed preferential flow paths (Figure 6). These flow paths formed a channel network stretching parallel to soil tillage along the steepest slope. The channel bottom, which was not a rill, was a sedimentary crust of constant thickness during the study.

At the top of the plots, where flow velocity was low because of reduced slope length, sediments were trapped in depressions or in channel bottoms and were remobilized by raindrop impacts only. Downslope, the

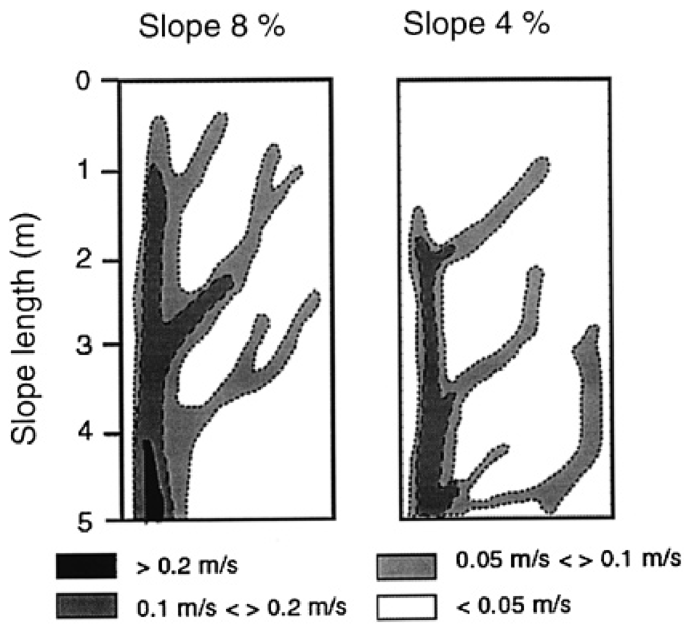

Figure 6. Maps of flow velocity on 4 per cent and 8 per cent slopes for 10 m^2 plots with 30 mm h^{-1} simulated rainfall intensity. Interpolation from 50 points of measurement

increase in flow velocity was responsible for the increase in particle remobilization and transport by rain-impacted flow. Remobilization was probably more efficient on steeper slopes, upon which sedimentation decreased. As the slope length increases, soil detachment rate decreases and erosion becomes detachment-limited.

CONCLUSION

In this study, the objective was, firstly, to analyse the effect of slope on interrill erosion for different plot sizes (1 to 10 m^2), and secondly, to discuss the combination of detachment and transport processes involved. Results show that erosion rate and runoff increase with increasing slope for the studied plot sizes. Sediment concentration does not increase with slope for 1 m^2 plots but increases for the larger plots (10 m^2). The results indicate that the lack of effect of slope steepness on sediment concentration for small plots is due to the reduced length of the plot used, which does not allow flow velocity to be significantly different for various slopes, i.e. erosion is transport-limited at the 1 m^2 plots. It therefore seems difficult to transfer erosion data obtained with such plots to a larger scale. The 10 m^2 plots (5 m slope length) may be a good compromise between experimental constraint and the inclusion of realistic processes.

The results show interactions between slope steepness, runoff and soil loss. They confirm that erosion models based on the multiplication of parameters, implying that factors are independent, are not appropriate for describing interrill sediment delivery. They also confirm that careless scale transfer of erosion data may lead to erroneous conclusions.

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